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REVIEW ARTICLE

Impact of potassium nutrition on postharvest fruit quality: Melon (*Cucumis melo* L) case study

Gene E. Lester · John L. Jifon · Donald J. Makus

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Abstract Among the many plant mineral nutrients, potassium (K) stands out as a cation having the strongest influence on quality attributes that determine fruit marketability, consumer preference, and the concentration of critically important human-health associated phytonutrients. However, many plant, soil, and environmental factors often limit adequate uptake of K from the soil in sufficient amounts to satisfy fruit K requirements during development to optimize the aforementioned quality attributes. The objectives of this review are 1) to summarize published study abstracts on the effects of soil and/or foliar K fertilization as well as diverse K forms, on fruit phytonutrient concentrations; and 2) to illustrate the important role of K forms on fruit quality with a case study of *Cucumis melo* L (muskmelon) fruit produced with optimal soil applied K . The muskmelon studies will compare commercial sources (forms) of K applied to examine seasonal effects (spring vs. autumn) and the number of foliar K applications during fruit development on fruit marketability (maturity, yield, firmness, soluble solids, sugars, relative sweetness), consumer preference attributes (sugar content, sweetness, texture), and phytochemical concentrations (K, ascorbic acid, and β-carotene concentrations). Numerous studies have consistently demonstrated that specific K fertilizer forms, in combination with specific application regimes, can improve fruit quality attributes. Potassium fertilizer forms in order of effectiveness (Glycine (Gly)-complexed K=$K_2SO_4 \geq KCl >$ no K> KNO_3) when applied wet (foliar or hydroponic) vs. dry (soil) were generally superior in improving fruit marketability attributes, along with many human-health nutrients. The muskmelon case study demonstrated that two K forms: Gly-complexed K and K_2SO_4, combined with a silicone-based surfactant, applied weekly, as a foliar spray, during fruit development, from both autumn and spring-grown plants, had the greatest impact on improving fruit marketability attributes (maturity, yield, firmness, and sugars), as well as fruit quality attributes (human-health bioactive compounds K, ascorbic acid, and β-carotene). Among several foliar applied K salts studied under field conditions so far, salts with relatively low salt indices appeared to have the greatest impacts on fruit quality when applied during the mid- to late-season fruit development periods.

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G. E. Lester (✉) · D. J. Makus
U.S. Department of Agriculture,
Agricultural Research Service,
Kika de la Garza Subtropical Agricultural Research Center,
2413 East Business Highway 83, Building 200,
Weslaco, TX 78596, USA
e-mail: gene.lester@ars.usda.gov

J. L. Jifon
Texas AgriLife Research,
Fruit and Vegetable Improvement Center,
Texas A&M System,
2415 East Business Highway 83,
Weslaco, TX 78596, USA

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Introduction

Potassium (K) is an essential plant mineral element (nutrient) having a significant influence on increasing many human-health related quality compounds in fruits and vegetables (Usherwood 1985). Although K is not a constituent of any organic molecule or plant structure, it is involved in numerous biochemical and physiological processes vital to plant growth, yield, quality and stress (Marschner 1995; Cakmak 2005). In addition to stomatal regulation of transpiration and photosynthesis, K is also involved in photophosphorylation, transportation of photoassimilates from source tissues via the phloem to sink tissues, enzyme activation, turgor maintenance, and stress tolerance (Usherwood 1985; Doman and Geiger 1979; Marschner 1995; Pettigrew 2008). Adequate K nutrition has also been associated with increased yields, fruit size, increased soluble solids and ascorbic acid concentrations, improved fruit color, increased shelf life, and shipping quality of many horticultural crops (Geraldson 1985; Lester et al. 2005, 2006; Kanai et al. 2007).

Even though K is abundant in many soils, the bulk of soil K is unavailable to plants, in part, because the pool of plant-available K is much smaller compared to the other forms of K in the soil. Potassium exists in several forms in the soil such as mineral K (90–98% of total), nonexchangable K, exchangeable K, and dissolved or solution K (K^+ ions), and plants can only directly take up solution K (Tisdale et al. 1985). Uptake in turn depends on numerous plant and environmental factors (Tisdale et al. 1985; Marschner 1995; Brady and Weil 1999). For instance, adequate soil moisture supply is necessary to facilitate diffusion of K (which usually accounts for >75% of K movement) to plant roots for uptake. Mass flow, which also accounts for some soil K transport, also requires sufficient water in the soil. Skogley and Haby (1981) found that increasing soil moisture from 10 to 28% more than doubled total soil K transport. Therefore, soil moisture deficits can limit soil K transport as well as uptake into the plant, thereby causing K deficiency.

Soil properties also have a strong influence on K availability. For instance, clay soils typically have high K-fixing capacities and thus often show little response to soil-applied K fertilizers because much of the available K quickly binds to clays (Tisdale et al. 1985; Brady and Weil 1999). Such K fixation can help reduce leaching losses, and be beneficial in the long-term as storage reservoirs of K for subsequent crops. Sandy soils, on the other hand tend to have a low K supplying power because of their low cation exchange capacities.

In calcareous soils, Ca^{2+} ions tend to exist in high concentrations and dominate clay surfaces, and even though this can limit K sorption and increase solution K, high concentrations of cationic nutrients (particularly Ca^{2+} and Mg^{2+}) tend to limit K uptake by competing for binding sites on root surfaces. Consequently, crops grown on highly calcareous soils can show K-deficiency symptoms even though the soil test may report sufficient K (Havlin et. al., 1999).

Potassium uptake also depends on plant factors, including genetics and developmental stage (vegetative versus reproductive stages; Rengel et al. 2008). In many fruiting species, uptake occurs mainly during vegetative stages, when ample carbohydrate supply is available for root growth and uptake processes. Competition for photoassimilates between developing fruits and vegetative organs during reproductive growth stages can limit root growth/activity and K uptake. Under such conditions, increasing soil K fertilization may not be enough to alleviate this developmentally-induced deficiency partly because of reduced root growth/activity during reproductive development and also because of competition from other cations for binding sites on roots (Marschner 1995).

In the literature, much confusion exists regarding the benefit of K fertilization due to different K forms utilized, soil vs. foliar applications, the environment (season), plus frequency of applications during fruit growth and development stages. This review will (1) summarize some of the published abstracts on K fertilization of several fruit crops, and (2) illustrate the influence of adequate K nutrition on fruit quality with a case study of supplemental foliar K fertilization of *Cucumis melo* L (muskmelon) grown on soil with seemingly adequate K content. Special attention is given to the effectiveness (comparison) of various K fertilizer sources, and soil vs. foliar application on fruit quality.

Fruit studies comparing K sources

Although many examples have been reported on the positive effects of K fertilization improving fruit disease control, yield, weight, firmness, sugars, sensory attributes, shelf-life, and human bioactive compound concentrations, the scientific literature also contains examples of studies with conflicting results of the beneficial effects of K fertilization on fruit quality (Table 1). These conflicting results cannot be resolved, but they can be explained by differences in modes of fertilization [soil applied (dry) vs. foliar, fertigation or hydroponic applied (wet)], and differences in forms of K fertilizer e.g. Glycine-complexed K, versus K_2SO_4, KCl, or KNO_3 from K fertilization. A review of published abstracts (Table 1), spanning the last 20 years, eight particular studies [apple (*Malus X Domestica;* Hassanloui, et al. 2004), cucumber (*Cucumis sativus;* Umamaheswarappa and Krishnappa 2004), mango (*Mangifera indica;* Rebolledo-Martinez et al. 2008), pear (*Prunus communis;* Johnson et al. 1998), bell pepper (*Capsicum annuum;* Hochmuth et al. 1994), strawberry (*Fragaria X ananassa;* Albregts et al. 1996), and watermelon (*Citrullus lanatus;* Locascio and Hochmuth 2002; Perkins-Veazie et al. 2003)] stand out, because of their conclusions: there is 'little or no change' (i.e. improvement) from K fertilization on fruit quality. However, except for the apple study, these studies have a common denominator in that potassium was applied directly to the soil and in many cases little information was given regarding timing of application with regard to crop phenology or soil chemical and physical properties such as pH, calcium and magnesium contents, and textures (sandy vs. clay). These properties are known to influence soil nutrient availability and plant uptake, and soil fertilizer K additions under such conditions may have little or no effect on uptake, yield and fruit quality (Tisdale et al. 1985; Brady and Weil 1999). In a number of studies involving several fruiting crops (e.g. cucumber, mango, and muskmelon) where soil-applied fertilizer K was compared to foliar K applications, the latter approach consistently resulted in improved fruit quality attributes whereas the former approach generally had little or no effects (Demiral and Koseoglu 2005; Lester et al. 2005; Lester et al. 2006; Jifon and Lester 2009; Table 1). Furthermore, in studies where several fertilizer K salts were evaluated, fruit quality improvements appeared to depend on timing of application as well as fertilizer K formulation. For instance, when mid- to-late season soil or foliar K applications were made using KNO_3 there were little or no improvements in fruit marketable or human-nutritional quality attributes and in some instances, these attributes were actually inferior compared to fruit from control plots (Jifon and Lester 2009).

Foliar Fertilization with different K salts: case studies with muskmelon (*Cucumis melo* L.)

As discussed above, plant and soil factors can limit soil-available, as well as plant uptake of K even though soil tests may report sufficient K. This situation is particularly acute for crops grown on highly calcareous soils whereby such uptake limitations can lead to K-deficiency symptoms, reduced yield and poor quality. In such cases where soil-applied fertilizers would be ineffective, due to high fixation, the only way to improve plant K uptake has been through foliar application of water-soluble K fertilizers, such as potassium chloride (KCl) or potassium nitrate (KNO_3). Controlled environment studies have indeed shown that supplementing soil-derived K supply with foliar K applications during the fruit development period can improve fruit quality and that differences may exist among K compounds for foliar feeding (Lester et al. 2005, 2006). To further explore the degree to which differences among some K salts may influence fruit quality, field studies were conducted near Weslaco, TX using a netted muskmelon (*Cucumis melo* L.) variety 'Cruiser'. Soils in this important fruit-producing region are predominantly calcareous with free calcium carbonate ($CaCO_3$), which tends to buffer soil pH to around 7.5 to 8.5. Base saturation is generally ~100%, and cation exchange is dominated by calcium. Average pre-plant soil concentrations of major cations were 7300, 660, 440, and 190 mg·kg^{-1} for Ca; K, Mg and Na respectively. All studies were conducted during the spring (February-May) growing season following standard commercial muskmelon production practices for this region (Dainello 1996). Foliar K treatments (Fig. 1) were applied weekly (between 0500 and 0800 a.m.) starting at fruit set, and continued till fruit maturation using K from various sources namely: potassium chloride (KCl), potassium nitrate (KNO_3),

Table 1 Review of published abstracts on the influence of potassium (K): effects by crop, K application, and K form on fruit attributes

Crop	K application	K form[a]	Attributes (improved)[b]	Reference[c]
Apple (*Malus X domestica*)	Soil	KCl;	Color, firmness, sugar;	(Nava et al., 2008);
		K_2SO_4;	Size, color, firmness, sugars;	El-Gazzar (2000);
		K_2SO_4	Wt. yield, firmness, sugars	Attala (1998)
Apple	Foliar	Unknown;	Size, color, firmness, sugars;	(Wójcik 2005);
		KCl	No change	(Hassanloui et al. 2004)
Banana (*Musa* sp.)	Soil	Unknown;	Quality;	Naresh (1999);
		KCl	Size, sugars, acid	(Suresh and Hasan 2002)
Citrus (*Citrus sinesis*)	Foliar	KCl, KNO_3;	No change;	(Haggag, 1988);
		unknown;	Yield, quality;	Dutta et al. 2003;
		K_2SO_4	Quality	(Shawky et al. 2000)
Citrus (*Citrus reticulata*)	Soil	Unknown;	Yield, quality;	(Lin et al. 2006);
		Unknown	Quality, shelf-life	(Srivastava et al. 2001)
Citrus (*Citrus reticulata*)	Foliar	$KCl>KNO_3$	Peel thickness, quality	(Gill and Singh 2005)
Cucumber (*Cucumis sativus*)	Soil	$K_2SO_4>KCl$;	Amino acids, quality;	Guo et al. 2004;
		KCl	No change	(Umamaheswarappa and Krishnappa 2004)
Cucumber	Foliar	$KCl>KNO_3$	"Quality", disease tolerance	(Magen et al. 2003)
Grapes (*Vitis vinifera*)	Soil	K_2SO_4	"Quality", sensory	(Sipiora et al., 2005)
Guava (*Psidium guajava*)	Soil	Unknown	Yield, weight, "quality"	(Ke and Wang 1997)
Guava	Foliar	$K_2SO_4>KCl$	Acidity, "quality"	Dutta (2004)
Kiwifruit (*Actinidia deliciosa*)	Soil	$K_2SO_4>KCl$	Firmness, acid, grade	He (2002)
Litchi (*Litchi chinensis*)	Foliar	KNO_3	Wt., yield,	(Ashok and Ganesh 2004)
Mango (*Mangifera indica*)	Soil	KNO_3	No change	Simoes (2001)
Mango	Foliar	KNO_3;	No effect; Texture, flavor, color shelf-life	(Rebolledo-Martinez et al. 2008);
		Unknown		Shinde (2006)
Muskmelon (*Cucumis melo*)	Soil	Unknown	Yield	(Demiral and Koseoglu 2005)
Muskmelon	Foliar	Gly-amino-K;	Firmness, vitamins;	(Lester et al. 2006);
		Gly-amino-K>KCl;	Firmness, sugars, vitamins	Lester (2006); (Jifon and Lester 2009)
		Gly-amino-K=$K_2SO_4>KCl>KNO_3$	Firmness, vitamins sugars; Yield, marketable fruit	
Nectarine (*Prunus persica*)	Soil	Unknown	Firmness, shelf-life, reduced cracking	(Zhang et al. 2008)
Okra (*Abelmoschus esculentus*)	Foliar	Naphthenate-K	Chlorophyll, protein, carotene	(Jahan et al. 1991)
Passionfruit (*Passiflora edulis*)	Hydroponic	K_2SO_4	Yield, seed number, "quality"	Costa-Araujo et al. 2006

Papaya (*Carica papaya*)	Soil	Unknown	Weight, sugars, "quality"	(Ghosh and Tarai 2007)
Pears (*Prunus communis*)	Soil	$K_2\ SO_4$	No change	(Johnson et al. 1998)
Phalsa (*Grewia subinaequalis*)	Foliar	$K_2\ SO_4$	Size, wt., "quality"	(Singh et al. 1993)
Pepper (*Capsicum annuum*)	Soil	KCl;	Little change;	(Hochmuth et al. 1994):
		$K_2\ SO_4$;	Pungency, "quality";	(Ananthi et al. 2004);
		$K_2\ SO_4$>KNO_3;	Pungency, yield, wt.;	(Golcz et al. 2004);
		$K_2\ SO_4$	"quality"	El-Masry (2000)
Pepper	Hydroponics	KNO_3	No change	(Flores et al. 2004)
Pineapple (*Ananas comosus*)	Soil	KCl	Vit. C, and reduced internal browning	(Herath et al. 2000)
Pomegranate (*Punica granatum*)	Foliar	$K_2\ SO_4$>KCl	Growth, yield, "quality"	(Muthumanickam and Balakrishnamoorthy 1999)
Strawberry (*Fragaria X ananassa*)	Soil;	KCl;	No change;	(Albregts et al. 1996);
	Fertigation	KCl>KNO_3	"quality"	(Ibrahim et al. 2004)
Strawberry	Hydroponics	$K_2\ SO_4$	Yield , total quality	(Khayyat et al. 2007)
Tomato (*Lycopersicon esculentum*)	Soil	KCl;	Lycopene;	(Taber et al. 2008);
		$K_2\ SO_4$;	"quality";	(Si et al. 2007);
		$K_2\ SO_4$;	Yield, earliness, quality	Hewedy (2000)
Tomato	Fertigation/ soilless	KCl>KNO_3;	Appearance, quality;	(Chapagain and Wiesman 2003);
		KCl>KNO_3;	Yield, "quality";	(Chapagain and Wiesman 2004);
		$K_2\ SO_4$;	Carotenoids, vit.E, antioxidants;	(Fanasca et al. 2006);
		Unknown;	Lycopene;	(Li et al. 2006);
		Unknown	"quality"	(Yang et al. 2005)
Tomato	Foliar	Unknown	Growth, protein, vit. C, sugar, acid	(Li et al. 2008)
Vegetables	Soil	$K_2\ SO_4$>KCl	Dry wt., vit. C	Ni et al. (2001)
Watermelon (*Citrullus lanatus*)	Soil	KCl	No change;	(Locascio and Hochmuth 2002);
		KCl	No change	(Perkins-Veazie et al. 2003)

[a] Forms from different studies are separated by a semi-colon; K form attributing to improved quality greater than another K form is indicated by the>symbol; [b] Attributes from different studies are separated by a semicolon, the word "quality" indicates the authors' listed no specific attributes, or the attributes were too numerous to list, [c] References from different studies are separated by a semi-colon

potassium sulfate (K_2SO_4), Gly-complexed K (glycine amino acid complexed K — Potassium Metalosate™, 20% K; Albion Laboratories, Inc, Clearfield, Utah), monopotassium phosphate (PeaK™, 24% K, Rotem BKG LLC, Ft Lee, NJ), and potassium thiosulfate (KTS™, 20% K, Tessenderlo Kerley Inc., Phoenix, AZ). Treatment solutions were formulated to supply the equivalent of ~4 kgK·ha^{-1} per week and each solution contained a non-ionic surfactant (Silwet L-77 at 0.3% v/v; Helena, Collierville, TN).

Leaf K concentrations measured during the fruit maturation period were significantly lower (~13 g·kg^{-1}) than the values measured before fruit set (~37 g·kg^{-1}). Leaf K concentrations were also lower than the recommended sufficiency ranges (20–40 g·kg^{-1}; Hochmuth and Hanlon 1995), even though preplant soil analysis indicated very high soil K concentrations (>600 mg·kg^{-1}). At fruit maturity, tissue (leaf, petiole, stem and fruit) K concentrations of foliar K-treated plants were on average ~19%

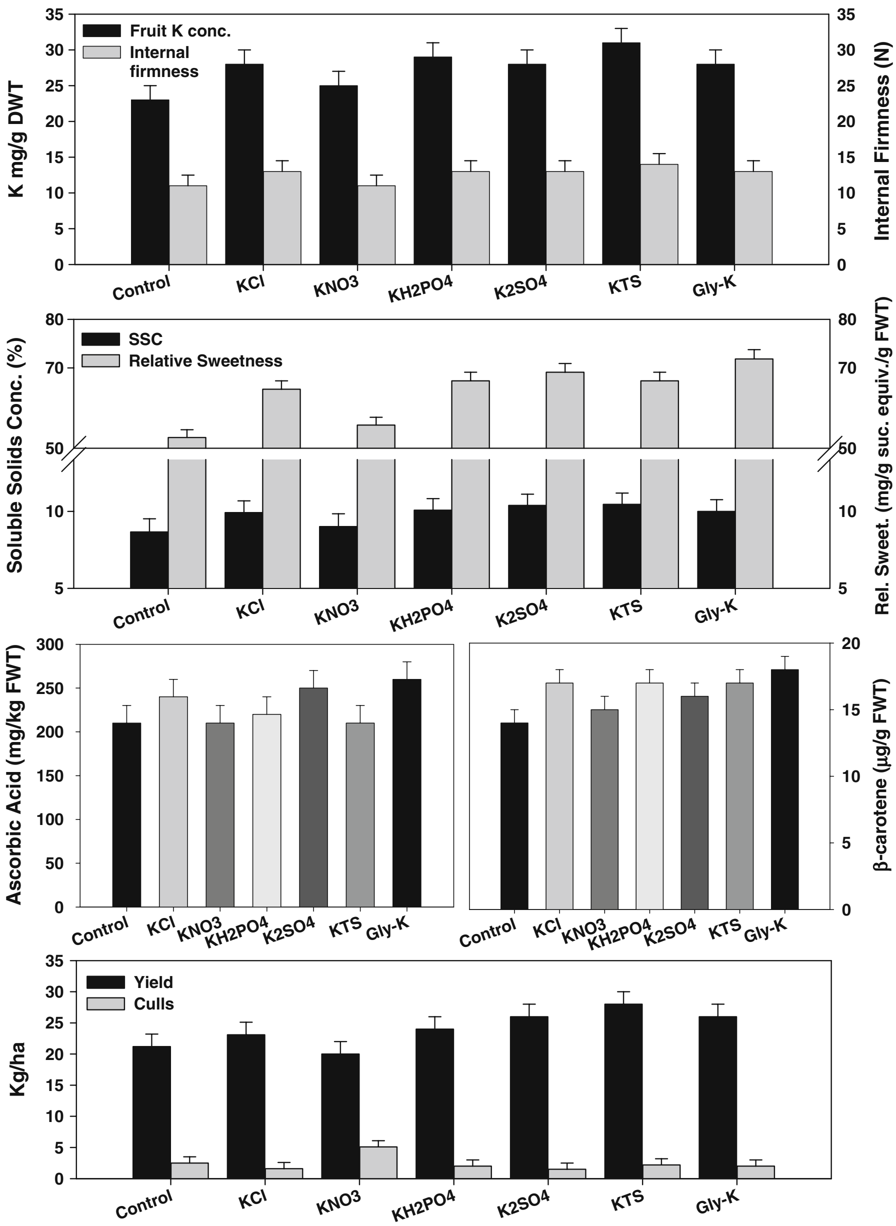

Fig. 1 Effects of various K fertilizer sources (potassium chloride — KCL, potassium nitrate — KNO_3, potassium sulfate — K_2SO_4, gylcine amino acid potassium — Gly —K, monopotassium phosphate — KH_2PO_4, and potassium thiosulfate — KTS) foliar applied weekly to field-grown, fruit-bearing muskmelon plants during fruit development on various marketability and quality attributes of fruit. All plants had sufficient soil fertilization. Relative sweetness=1.8 (mg/ g FWT fructose)+0.7 (mg/g FWT glucose)+1.0 (mg/g FWT sucrose). Data are means± SD and are separated by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at $P \leq 0.05$ (Jifon and Lester, 2009)

higher than those of control plants. This observation suggests that plant K uptake from this calcareous soil was not sufficient to maintain tissue K concentrations within sufficiency levels, and that the K supplying power of this soil may be low even though pre-plant soil K content was high. The low K supplying capacity of this soil is further indicated by the high pH and high Ca and Mg concentrations since these conditions are known to suppress soil K availability and plant uptake (Marschner 1995; Brady and Weil 1999). Fruit quality parameters (soluble solids concentration, total sugars, sweetness, and the phytochemical compounds — ascorbic acid and beta-carotene) responded positively to foliar K applications (Fig. 1). However, no clear trends were apparent with regard to the most suitable salt for all quality parameters except for KNO_3 whose effects were nearly always statistically similar to those of the control treatments. The lack of significant differences between controls and KNO_3-treated plants was probably related to timing of treatment applications with respect to crop phenology. Treatments were applied during the reproductive growth stages (mid- to late-season), and foliar fertilization with KNO_3 significantly increased leaf N concentrations (~30%) compared to the other K salts; the resulting stimulation of vegetative growth at the expense of roots and fruits probably accounted for the marginal effect on fruit quality through competition for assimilates (Way and While 1968; Davenport 1996; Neuweiler 1997; Keller et al. 1999; Wade et al. 2004). Fruit mesocarp tissue firmness, a good indicator of shipping quality, texture and shelf life (Harker et. al., 1997), was improved by foliar K applications. This may be related to increased tissue pressure potential (Lester et al. 2006). Foliar K-treated plots had slightly higher yields (Fig. 1), however, this effect was only significant in one of the 3 years, and with one K salt (potassium thiosulfate). Additionally, the average number of cull fruit with defects such as poor external rind (net) development or small size was generally higher in plots treated with foliar KNO_3 than in plots treated with the other K forms (Fig. 1).

In addition to plant and environmental factors, critical properties of potential K salts for foliar nutrition are solubility, salt index (SI) and point of deliquescence (POD). A suitable balance among these properties is required to maximize nutrient absorption into plant tissues and to minimize phytotoxicity effects. Highly soluble salts are preferred since this means faster cuticular penetration and smaller volumes of solution needed for application. The salt index of a fertilizer material is defined as the ratio of the increase in solution osmotic pressure produced by the fertilizer material to that produced by the same mass of $NaNO_3$ (Mortvedt 2001). The SI gives an indication of which fertilizer salts (usually those with higher SI) are most likely to cause injury and compares one fertilizer formulation with others regarding the osmotic (salt) effects (Mortvedt 2001). The SI of some common K salts are, KCl, 116; KH_2PO_4, 8.4; K_2SO_4, 43; potassium thiosulfate, 68 (Mortvedt 2001).

A common production problem not observed in this study, which is likely temperature related, is the foliar ‘burning’ effect, which is frequently observed when using foliar applied salts such as KCl (Swietlik and Faust 1984). Burning of leaves occurs when salts accumulate on the surface and are not absorbed. Rates of absorption are highest when relative humilities are 80% or higher (Schonherr and Luber, 2001). In this field study leaf ‘burn’ symptoms were not observed with any of the treatments, in part, because all treatments were applied between 0500 and 0800 when high air relative humidities, (>80%), low air temperatures (<25°C) and low wind speeds ($<0.45\ m.\ s^{-1}$) prevailed.

Point of deliquescence of a foliar fertilizer salt determines the rate at which the applied salt is absorbed by plant tissues. Point of deliquescence is the humidity over a saturated salt solution containing solid salt (Schönherr and Luber 2001). If air humidity is higher than the POD, salts will remain dissolved in solution and absorption will proceed rapidly. However, when air humidity is below the POD (i.e. drier air), salts will re-crystallize, resulting in slower uptake and increasing the potential for salt injury. Reported POD values for some common K salts are K_2CO_3, 44%; KCl, 86%; KNO_3, 95%; and KH_2PO_4, 97% (Schönherr and Luber 2001). Several studies have shown that phytotoxicity effects are common when compounds such as KCl, with high salt indices and relatively high point of deliquescence, are used and this is more pronounced when they are applied under conditions of high temperature and/or low air humidity (Schönherr and Luber 2001).

K fertilizer application: seasonal influence and silicone-based surfactant

Muskmelon fruit firmness (external — under the epidermis, at the equatorial region; and internal middle-mesocarp — at the equatorial plane, using a penetrometer) from autumn and spring fruit-bearing plants, sprayed with K, was higher than that of fruit from control plants (no foliar K) regardless of season, surfactant use, or K form (Fig. 2). Similar beneficial effects of foliar K, from KH_2PO_4, on tomato fruit (*Lycopersicon esculentum* Mill.) firmness has been shown (Chapagain and Wiesman 2004), but the mechanisms for improved firmness were not discussed. Increased melon fruit firmness from exogenously-applied K is not due to improved membrane integrity or cell wall stability, as is the case with exogenously-applied calcium (Lester and Grusak 1999), since K does not become part of any structural component of plant tissues as does Ca (Cooke and Clarkson 1992). The increase in melon fruit firmness resulting from foliar applied K is increased (more positive) fruit-tissue

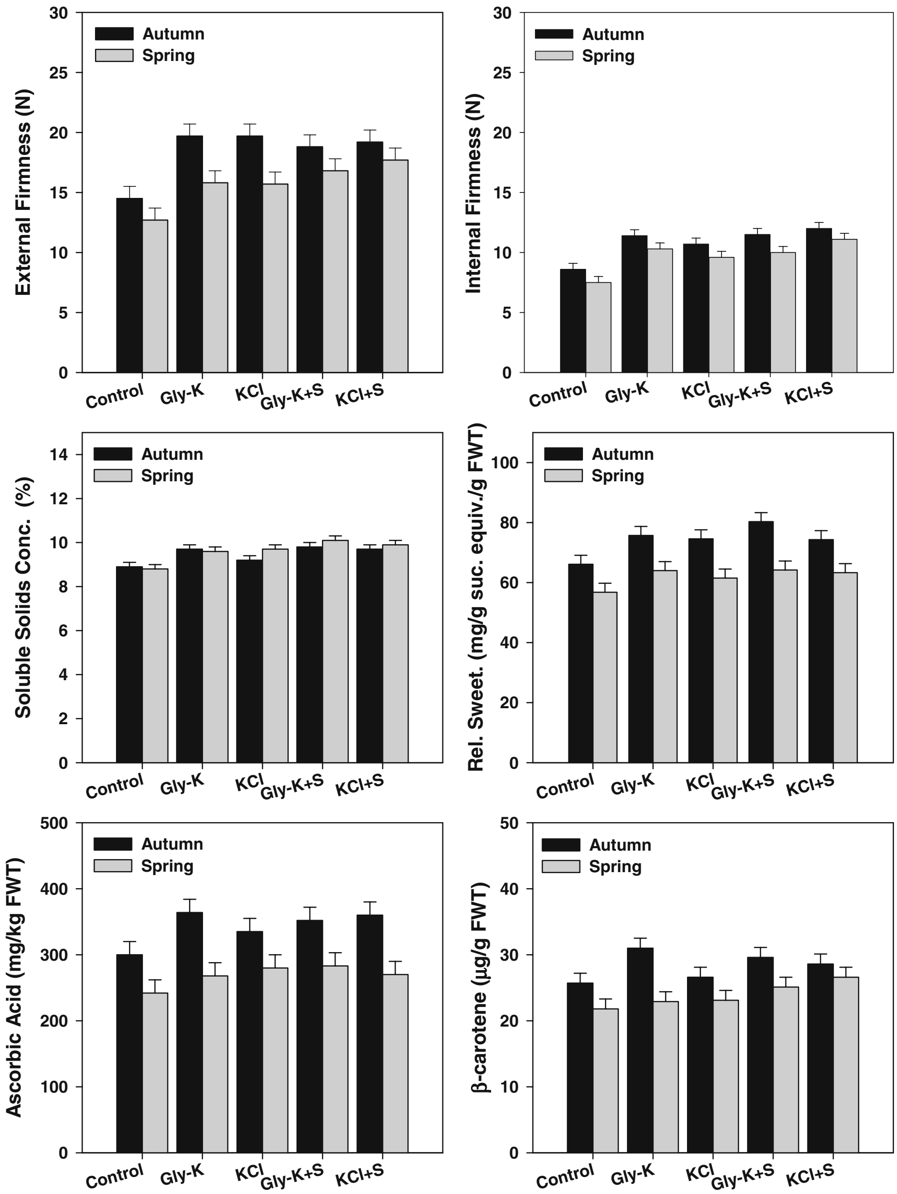

Fig. 2 Effect of growing season (autumn or spring) and two sources of K (potassium chloride — KCL, gylcine amino acid potassium —Gly —K) with or without a silicon-based surfactant (S) foliar applied weekly to glasshouse-grown fruit-bearing muskmelon plants during fruit development on various marketability and quality attributes of fruit. All plants had sufficient soil fertilization. Relative sweetness=1.8 (mg/ g FWT fructose)+0.7 (mg/g FWT glucose)+1.0 (mg/g FWT sucrose). Data are means±SD and are separated by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at $P \leq 0.05$ (Lester et al. 2006)

pressure potential (ψ_p) (Table 2). Mesocarp tissue ψ_p was significantly higher in all K-treated, compared to non-treated control fruits. Addition of surfactant increased the effect of foliar K application on mesocarp tissue ψ_p (+46% and +150% for Gly amino acid complexed K (Gly-K) and KCl, respectively), although surfactant use was not always associated with increased fruit firmness. A significant positive correlation was observed between fruit-tissue ψ_p and internal fruit firmness (r=0.259; P=0.01). The increased ψ_p of K-treated fruit, compared to controls, resulted, at least in part, from greater accumulation of other osmolytes (e.g. sugars; Fig. 2) in addition to increased K concentrations in fruit cells (Lester et al. 2006). Since there were no differences in tissue water potential (ψ_w), a more negative solute potential (ψ_s) resulted in higher ψ_p ($\psi_p = \psi_w - \psi_s$) values in K-treated, compared to control fruits (Lester et al. 2006). Pressure potential was found to be positively correlated with SSC (r= 0.232; P=0.01), total sugars (r=0.276), fruit sucrose and glucose concentrations (P=0.05) (Lester et al. 2006). Positive correlations among tissue solute concentration, turgor and firmness have also been reported for potato (*Solanum tuberosum* L.) tubers (Beringer et al. 1983) and apples (Tong et al. 1999).

Fruit sugars as measured by soluble solids concentrations and relative sweetness were higher in K-treated compared to control fruit in both autumn and spring grown fruit (Fig. 2). Fruits from plants treated with Gly-K also tended to have slightly greater soluble solids concentrations and relative sweetness levels than those treated with KCl regardless of silicone-based surfactant use or season. Previous studies on supplemental K fertilization have reported a variety of responses including an increase in fruit sugar levels (e.g. Chapagain and Wiesman 2004; Daugaard and Grauslund, 1999; Johnson et al. 1998), no effect on fruit SSC (Flores et al. 2004; Hartz et al. 2001) and improved yields (Hartz et al. 2005). Hartz et al. (2001, 2005) also found that K fertigation reduced the incidences of yellow shoulder and internal white tissue disorders in tomato but did not influence fruit SSC or juice color. Hartz et al. (2001, 2005) attributed the absence of any response of fruit SSC to other overriding factors, such as cultivar and irrigation management, which potentially masked any K effects. Lin et al. (2004) found that supplemental K fertilization of melon in soilless culture increased fruit sucrose content but had no effect on fruit fructose and glucose concentrations. However, in the Lester et al., (2006) study, netted muskmelon fruit sucrose, glucose and fructose levels were increased by supplemental foliar K fertilization. It is worth noting that foliar Gly-complexed K treatments without surfactant had higher fruit fructose concentrations than the Gly-complexed K treatments with a silicone-based surfactant. A plausible explanation for this observation maybe silicone-based surfactant interference with the catalytic role of amino acids on invertase activity. Silicone-based reagents synthesize aminophosphonates (Boduszer and Soroka, 2002) which act as antagonists of amino acids, inhibiting enzyme metabolism affecting the physiological activity of the cell (Kafarski and Lejcak 1991). Acid invertase (EC 3.2.1.26), found in melon fruits (Lester et al. 2001) is responsible for sucrose hydrolysis to fructose and glucose. Amino acids are catalysts in this hydrolysis reaction (Quick and Schaffer 1999). It is likely the silicone-based surfactant interfered with the catalytic activity of the amino acid cofactor, thus down-regulating acid invertase allowing sucrose phosphate synthase (EC 2.3.1.14), the sucrose-synthesizing enzyme in melons (Lester et al. 2001), to remain active. Sucrose phosphate synthase specifically utilizes K as a cofactor to synthesize sucrose from glucose and fructose (Lester et al. 2001). The relative levels of sucrose and fructose in fruit also have important implications for consumer preference (relative sweetness) since fructose is perceived to be up to 80% sweeter than sucrose.

Table 2 Influence of weekly supplemental foliar K — glycine amino acid-potassium (Gly-K) and potassium chloride (KCl) applied with or without a surfactant (S), to fruit-bearing plants grown with adequate soil K concentrations, on muskmelon fruit tissue pressure potential (Lester et. al., 2006)

Treatment	Fruit Pressure ψ_p (MPa)[a]
Gly-K	−0.018b[b]
KCl	−0.034c
Gly-K+S	0.003a
KCl+S	0.011a
Control	−0.064d

[a] The more positive the pressure potential the firmer the fruit.
[b] Means followed by the same letter are not significantly different by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at *P≤0.05*

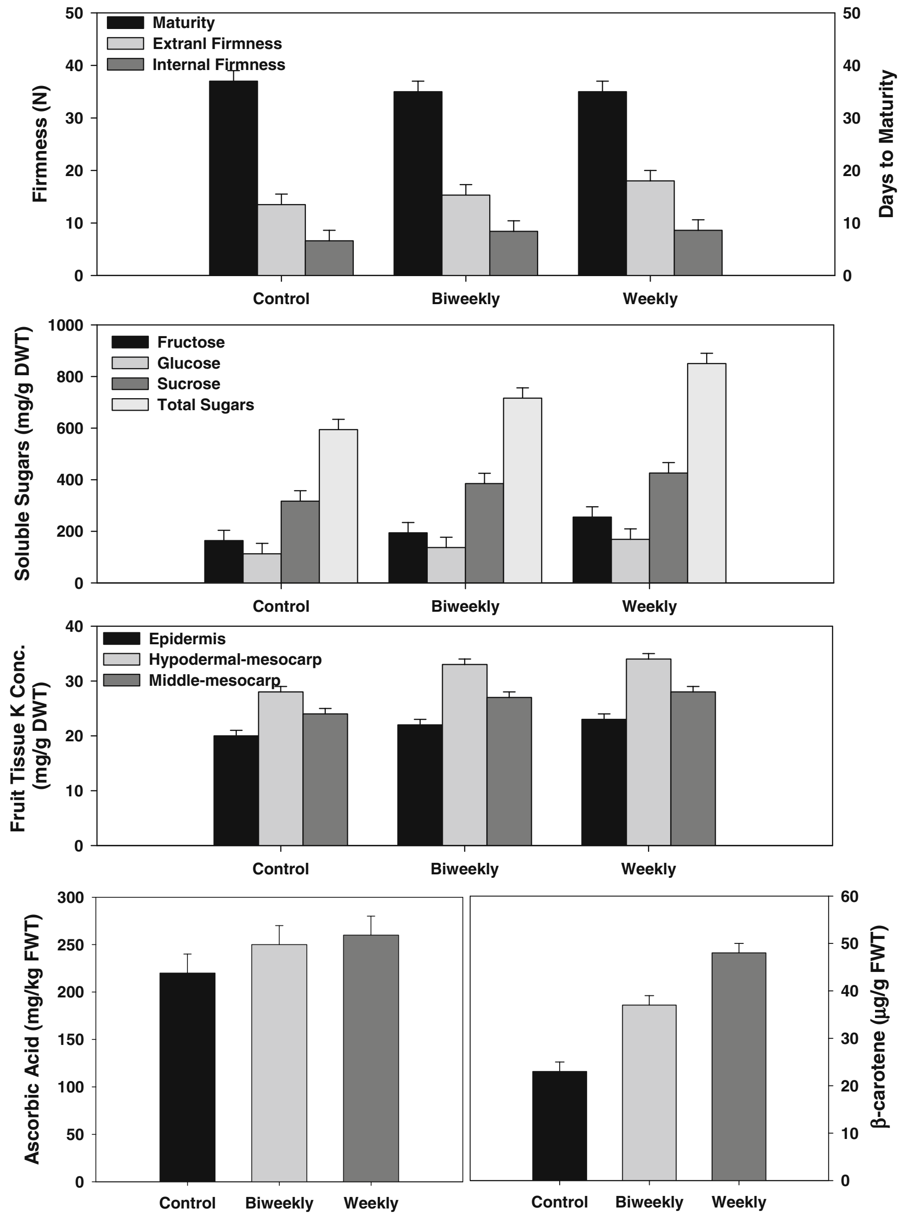

Fig. 3 Effect of number of foliar applications of K (gylcine amino acid potassium) applied to glasshouse-grown, fruit-bearing muskmelon plants during fruit development on various marketability and quality attributes of fruit. All plants had sufficient soil fertilization. Data are means ±SD and are separated by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at $P \leq 0.05$ (Lester et al. 2005)

Total ascorbic acid and β-carotene were generally higher in fruits treated with K than in control fruits (Fig. 2). However, there were no consistent K source effects on these quality parameters. The beneficial effects of supplemental K probably resulted from a combination of improved leaf photosynthetic CO_2 assimilation, assimilate translocation from leaves to fruits, improved leaf and fruit water relations, increased enzyme activation and substrate availability for ascorbic acid and β-carotene biosynthesis all associated with adequate K nutrition (Hopkins 1963; Gross 1991). At present, it is unclear how high K concentrations in melon fruit increases ascorbic acid and beta-carotene concentrations, but increased synthesis through enzyme activation is a possible mechanism. In general, use of a surfactant increased fruit tissue concentrations of ascorbic acid and β-carotene (Fig. 2). However, the surfactant effect was not always consistent with both K forms; requiring further investigations into various surfactants applied with and without K foliarly to fruit-bearing plants. Use of specific foliar applied K forms, as a means to improve the antioxidant capacity (ascorbic acid and β-carotene, respectively) of melon fruits is a readily applicable, low-technology approach to improve the human wellness attributes of current commercially produced melon cultivars.

The beneficial effects of supplemental foliar K applications to fruit-bearing plants on melon fruit quality parameters were consistently positive regardless of growing season — spring or autumn. However, fruit produced in autumn had higher fruit firmness, ascorbic acid, β-carotene, total sugars and SSC (Fig. 2). Mechanisms for the improved quality parameters in autumn- compared to spring-grown fruit are still uncertain since average daily temperatures and cumulative heat units were slightly higher in autumn (~33°C and 728, respectively) than in spring (~28°C, 601). Cumulative photosynthetic photon flux during fruit development (from pollination to final harvest) was higher in spring (982 $mol{\cdot}m^{-2}$) than in autumn (637$mol{\cdot}m^{-2}$). New findings suggest that weather and climate play key roles in the human-health bioactive compounds in fruits (Lester 2006). These studies highlight how global climate change might affect the nutritional properties of food crop and how, through the use of foliar applied K, growers may counteract these effects.

Number of foliar K applications

Supplemental foliar K applications resulted in earlier maturity of treated fruit compared to controls (Fig. 3). While this important marketability trait is not reported in K-treated fruit and the mechanisms for this effect are unclear, similar K-induced effects on fruit K concentrations and firmness have been reported (Chapagain and Wiesman 2004). Earlier maturity is a desirable economic trait in muskmelon production regions where adequate solar radiation flux can permit sufficient soluble solids accumulation in fruits before full-slip (abscission). Also, increased fruit firmness realized with weekly K foliar applications>biweekly applications>no foliar K application (Fig. 3), results in a melon fruit having an extended shelf-life which is another important marketability trait.

Fruit K contents resulting from the supplemental foliar application, increasing with weekly applications >biweekly applications of K compared to control fruit, was accompanied by increased fruit sugar levels (Fig. 3). Leaf photosynthesis rates are reported to increase with increased leaf K concentrations and this could be one mechanism of increased sugar contents in fruit (Terry and Ulrich 1973; Peoples and Koch, 1979; Pettigrew 1999). However, leaf photosynthesis rates measured during the melon fruit maturation were similar among control and K-treated fruits (data not shown). Increased phloem loading, transport rate and/ or unloading of sugars could also account for the increased fruit sugar levels, although it is uncertain whether this is a direct effect (enhanced phloem unloading in fruits) or an indirect effect (e.g. enhanced sucrose synthesis in source leaves) (Doman and Geiger 1979; Peel and Rogers 1982). (Ache et al. 2001) provided evidence for faba bean (*Vicia faba* L.) indicating that K^+ channels are involved in sugar unloading. Potassium-induced increases in fruit sugar levels have also been reported in hydroponically grown muskmelon plants (Lin et al. 2004) however, the mechanism for this effect was also unclear. Although a threshold tissue K concentration for attaining optimum fruit sugar levels has not been established, our melon data (Lester et al. 2005 and 2006; Jifon and Lester 2009) provide additional evidence that fruit sugar concentrations can be increased through supplemental foliar K sprays.

Antioxidants ascorbic acid, derived from glucose (Hopkins 1963), and beta-carotene significantly increased with weekly K applications>biweekly applications>no foliar K application (Fig. 3). Of the two antioxidants, beta-carotene dramatically responded to K foliar fertilizations increasing 70% and 100% with biweekly and weekly applications respectively. A benefit to the plant for having heightened levels of antioxidants is improved plant tolerance to various environmental stresses such as drought, low temperature, salinity, and sun burning all of which trigger cellular oxidative stress (Hodges et al. 2001; Cakmak 2005). The mechanism for K-induced oxidative stress tolerance is through increased ascorbic acid and beta carotene antioxidant activity. Ascorbic acid acts as an antioxidant by donating electrons and hydrogen ions thus reducing reactive oxygen species or free radicals. And beta-carotene is an accessory pigment in green tissues involved in photon capture protecting chlorophyll molecules from photo-oxidation due to excessive light thus reducing bleaching and sun burning and exhibits good radical-trapping antioxidant behavior under low (2%) oxygen conditions in fruit and root/tuber tissues (Gross 1991).

In melon fruit, the enzyme lipoxygenase (EC 1.13.11.12) has been associated with cellular membrane breakdown and fruit senescence through enhanced production of free radicals, however, this effect is minimized in fruit with high beta-carotene concentrations (Lester 1990). Ascorbic acid and beta-carotene also play similar important roles as antioxidants in humans when consumed in diets. Enhancing their accumulation in fruits, through carefully-timed, controlled K foliar fertilization to fruit-bearing plants will enhance the human wellness potential of melons (Lester and Eischen 1996; Larson 1997).

Conclusions

Supplementing soil K supply with foliar K applications to fruit-bearing plants improves fruit quality by increasing firmness, sugar content, ascorbic acid and beta-carotene levels. Among the K salts, KNO_3 has little or no beneficial effects on fruit quality when applied during fruit maturation, perhaps due to a dilution effect resulting from N stimulation of vegetative growth at the expense of roots and fruits. Perhaps foliar fertilization KNO_3 would be more beneficial during the vegetative growth stages when N is most needed for development of leaves with high photosynthetic capacity. The fruit quality improvements summarized in this review were obtained by implementing a simple low cost management tool that growers can easily adopt; resulting in nutritionally enrich fruits which, at little or no extra retail cost, benefits the consumer. Future research is needed to validate these findings in commercial field trials under different production environments (temperate vs. tropical) and productions systems (conventional vs. organic), and evaluate the effect of different K forms (glycine amino acid complexed K versus potassium chloride and others) on marketable quality and health-bioactive compound quality attributes of various fruits.

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